VISUALIZING THE EFFECT OF THE CORIOLIS AND FRICTIONAL FORCES ALONG A COASTLINE IN DOPPLER SODAR DATA

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1. INTRODUCTION

The Illinois Department of Nuclear Safety (IDNS) owns and operates a Doppler SODAR along the western shoreline of Lake Michigan. The Doppler SODAR is located about one kilometer inland near the city of Waukegan. This paper illustrates the effect of the Coriolis force as seen in the Doppler SODAR data and shows the difference between the lake and land frictional forces.

2. BACKGROUND

Wind direction changes in the boundary layer have important repercussions on the dispersion pattern of effluents and emergency response efforts. In the boundary layer, surface features interfere with airflow and cause wind velocities to decrease. The boundary layer wind can be illustrated by starting with the geostrophic wind (Figure 1). The air would be flowing along the isobars with a balance between the pressure gradient and Coriolis accelerations. If surface friction is introduced the wind velocity will decrease. As the wind velocity decreases, the Coriolis acceleration will decrease, resulting in a wind direction toward the lower pressure because of the greater pressure gradient acceleration. The resulting airflow reaches a balance where acceleration from the pressure gradient is matched by the combined Coriolis acceleration and frictional deceleration. The boundary layer wind is therefore neither parallel nor perpendicular to the isobars, but is between, with the wind direction determined by the amount of friction exerted by the surface.

Visualizing the boundary layer then, the wind direction shifts clockwise with increase in height. This is shown in Figure 2(a) where the angle θ in the x-y plane increases in a counterclockwise fashion as the ground level is approached. This has two important emergency response ramifications. First, it is apparent that the wind direction at the base of the stack shown in Figure 2(a) may not be a true indication of the direction of travel of effluents released from the top of a tall stack. Thus wind direction measurements made near the surface may be misleading in terms of the actual direction the effluents may take as they leave the stack. Second, as effluents are carried downwind, they will diffuse outwardly in the y-direction and vertically in the z-direction. As effluents diffuse vertically in the boundary layer, they will encounter different wind directions at different heights. Thus the pattern of dispersion downwind frequently will not be symmetrical to the x-axis of the wind direction at the top of the stack, but instead will tend to become skewed. This situation is illustrated in Figure 2(b), as one looks downward into the x-y plane. The amount of skewness depends upon the relative position of the top of the stack in the boundary layer.

The IDNS Doppler SODAR is located along Lake Michigan, where surface friction between the land and lake is noticeably different. This study was conducted to document what wind direction changes occur in the boundary layer of the near-shore environment and how these frictional differences affect wind direction.

3. SODAR DATA AVERAGING

Doppler SODAR data from 1995 and 1996 were used in this study. The Doppler SODAR data set for this period contains over 70,000 fifteen-minute averages. Each fifteen-minute average was screened for invalid data, which were removed. The Doppler SODAR data contain wind speed and wind direction data in 30-meter increments from 60 to 600 meters above ground level. A UVW wind sensor at 10 meters is also included in the data.

An average profile of wind direction was obtained for each of the 16 meteorological sectors. The average profiles were obtained by determining the meteorological sector of the 300-meter wind

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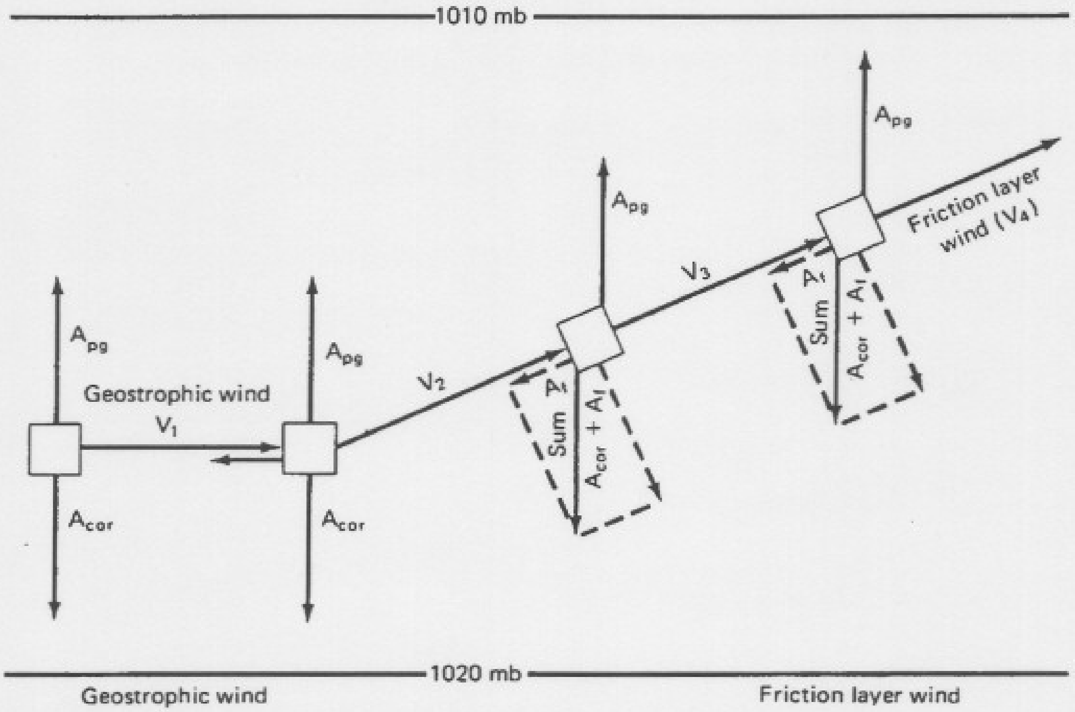

Figure 1. Within the boundary layer, winds result from a balance between the pressure gradient acceleration (A_{pg}) and the sum of the Coriolis acceleration (A_{cor}) and frictional deceleration (A_f).

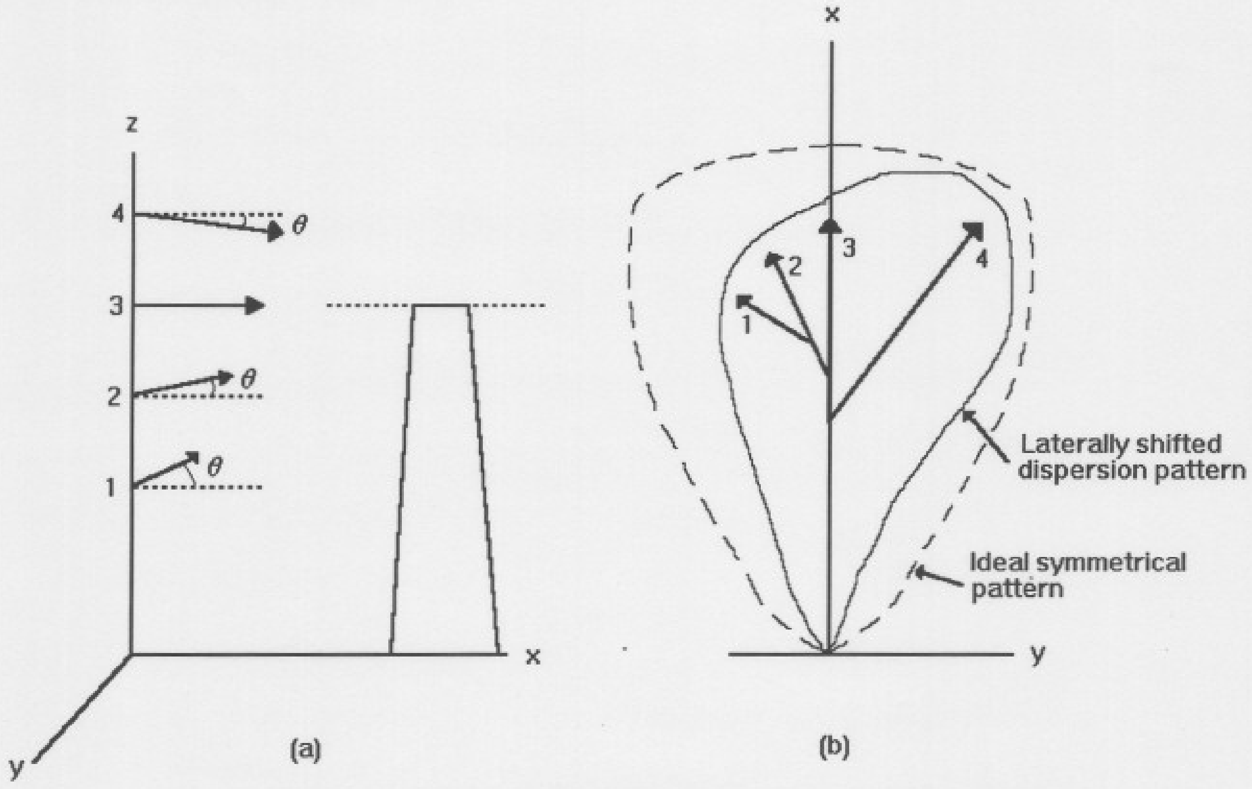

Figure 2. Effect of frictional forces in the boundary layer on the wind direction at various altitudes.

direction and averaging all the wind directions at each height for all the fifteen-minute averages. For example, all the fifteen-minute averages that had a 300-meter wind direction from the east were stored, and the data at each height interval were averaged to obtain a profile from the east. If the 300-meter wind direction was missing, the fifteen-minute average was omitted. The average wind speeds and vertical velocities of each profile were also obtained.

4. RESULTS

Using the 300-meter wind direction to determine the meteorological sector, Figure 3 shows the average wind direction profiles by sector for 1995-1996 for all wind speeds and conditions. Figure 4 shows isopleths of vertical velocity for the profiles given in Figure 3. On both Figure 3 and Figure 4, the 10-meter data are depicted in the center. As one travels away from the center, the data progress in height by 30-meter increments. As a guide, the dashed inner ring depicts the 300-meter data, and the outer ring depicts the 600-meter data. Symbols on each curve of Figure 3 are plotted according to the wind direction in a 0 to 360 degree fashion. To help illustrate the frictional differences, the area under the curve of each profile was shaded up to the 300-meter level. Figure 3 shows three particular items of interest.

First, the clockwise shift in wind direction with increasing height is clearly seen, particularly with winds having a more westerly component. This is due to the increase of friction caused by the surface which offsets the Coriolis acceleration.

Second, the shaded area under each curve is generally the greatest for winds with an easterly component. This translates to increased wind direction changes with height when winds are coming from Lake Michigan. Two explanations may account for this: 1). Easterly winds encounter little friction as they travel across Lake Michigan. When the wind encounters the shoreline, surface friction is increased and a greater wind direction change with height occurs. 2). On the average, the wind speeds for the easterly component winds are not as great compared with westerly component winds (see Figure 5). In light winds the frictional forces can have a greater impact upon the changes in wind direction.

Third, and most interesting, the profiles above 300 meters show that winds from the south-southwest clockwise through northwest sectors continue a uniform clockwise turning, winds from the east clockwise through south sectors have an increased clockwise turning, but winds from the north clockwise through east-northeast sectors begin to turn counterclockwise. To better illustrate the differences above 300 meters, Figure 6 shows the same profile curves as in Figure 4, except that the curves are plotted in the same direction. Figure 7 shows the Figure 4 data plotted linearly to indicate the actual number of degrees the wind direction changes with height. The difference in the profile curves above 300 meters is due to a mesoscale pressure ridge parallel to the shoreline which develops as onshore winds encounter the shoreline surface friction. The decreased surface winds and increased vertical motions (see Figure 4) cause a damming effect which affects the winds in the 300- to 600-meter levels. (Figure 5 shows the winds above 300 meters decreasing with height.) As these winds approach the pressure ridge, they are deflected away from the ridge (see Figure 8). If a southeast wind comes onshore, the pressure ridge deflects the wind to a more southerly (or clockwise) direction. If a northeast wind comes onshore, the pressure ridge deflects the wind to a more northerly (or counterclockwise) direction.

Although not presented here, wind profiles were also obtained for periods at night (7PM - 7AM) and for 90-meter wind speeds above and below 5 m/s. This resulted in five other wind profiles: all data with speeds less than 5 m/s, all data with speeds greater than 5 m/s, all nighttime data, all nighttime data with less than 5 m/s, and all nighttime data with speeds greater than 5 m/s. Nighttime cases were used to eliminate the effect of any lake breezes and solar heating effects. The speed classes were used to see if there was a difference in the frictional drag caused by the shoreline. These five wind profiles look very similar to the figures presented here, for all time periods and wind speeds, including the differences above 300 meters.

5. DISCUSSION

Emergency response personnel need to have a good understanding of the meteorology along a coastline. If radioactive effluents are released along a coastline, the height of the stack as well as any plume rise can be key factors for determining where effluents will travel. Emergency responders could use the figures presented here to make accurate predictions about plume direction changes caused by the Coriolis effect. Figure 9 shows several plumes turning slightly clockwise due

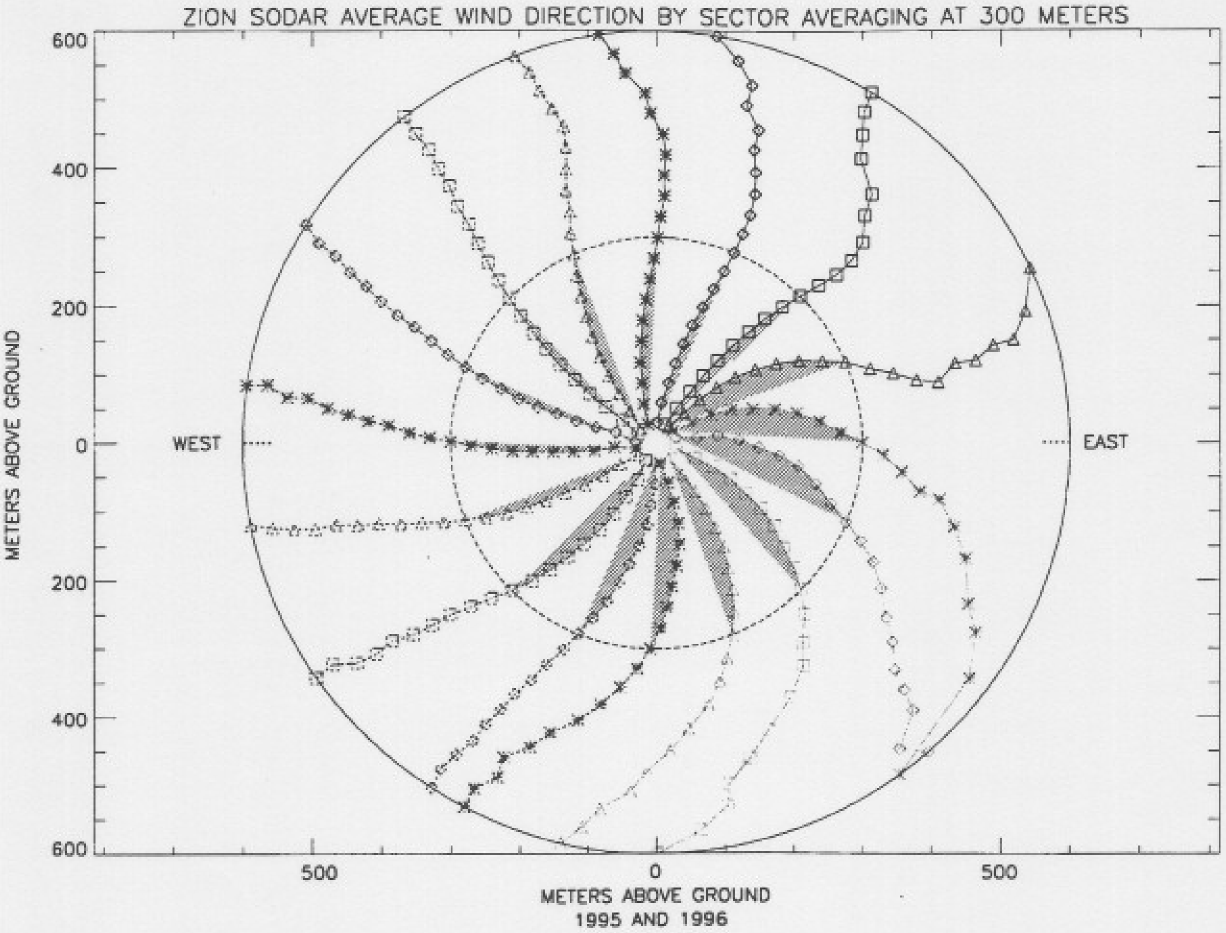

Figure 3. IDNS Doppler SODAR average wind profiles for 1995-1996 by sector averaging using the 300-meter wind direction. Data are plotted according to direction (0 to 360). 10-meter data are depicted near the center, 300-meter data are depicted on the dashed inner ring, and the 600-meter data are depicted on the outer ring. Data are plotted at 30-meter intervals. Areas under each profile curve were shaded to illustrate frictional differences.

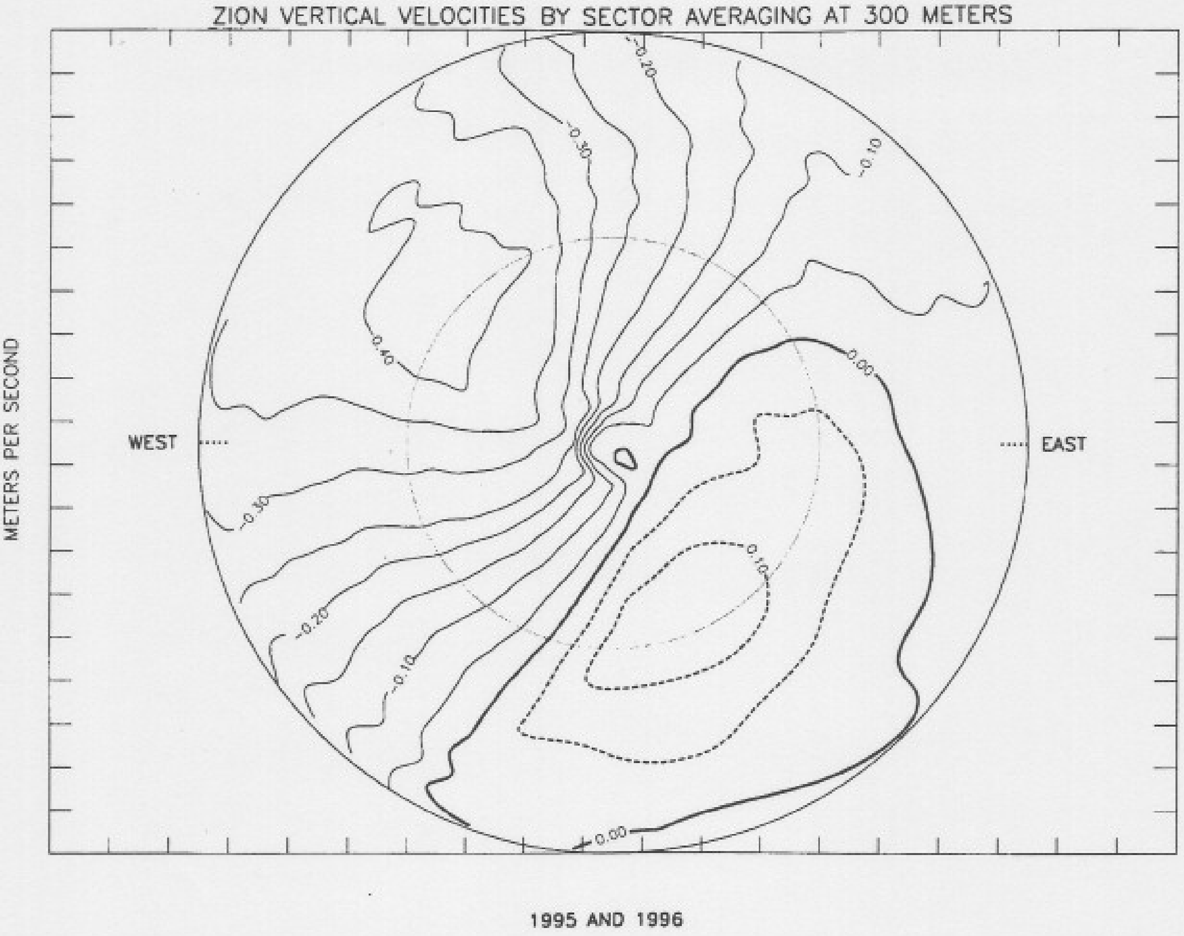

Figure 4. IDNS Doppler SODAR average vertical velocity data in meters per second for the wind profiles in Figure 3. Solid lines indicate descending air and the dashed lines indicate ascending air.

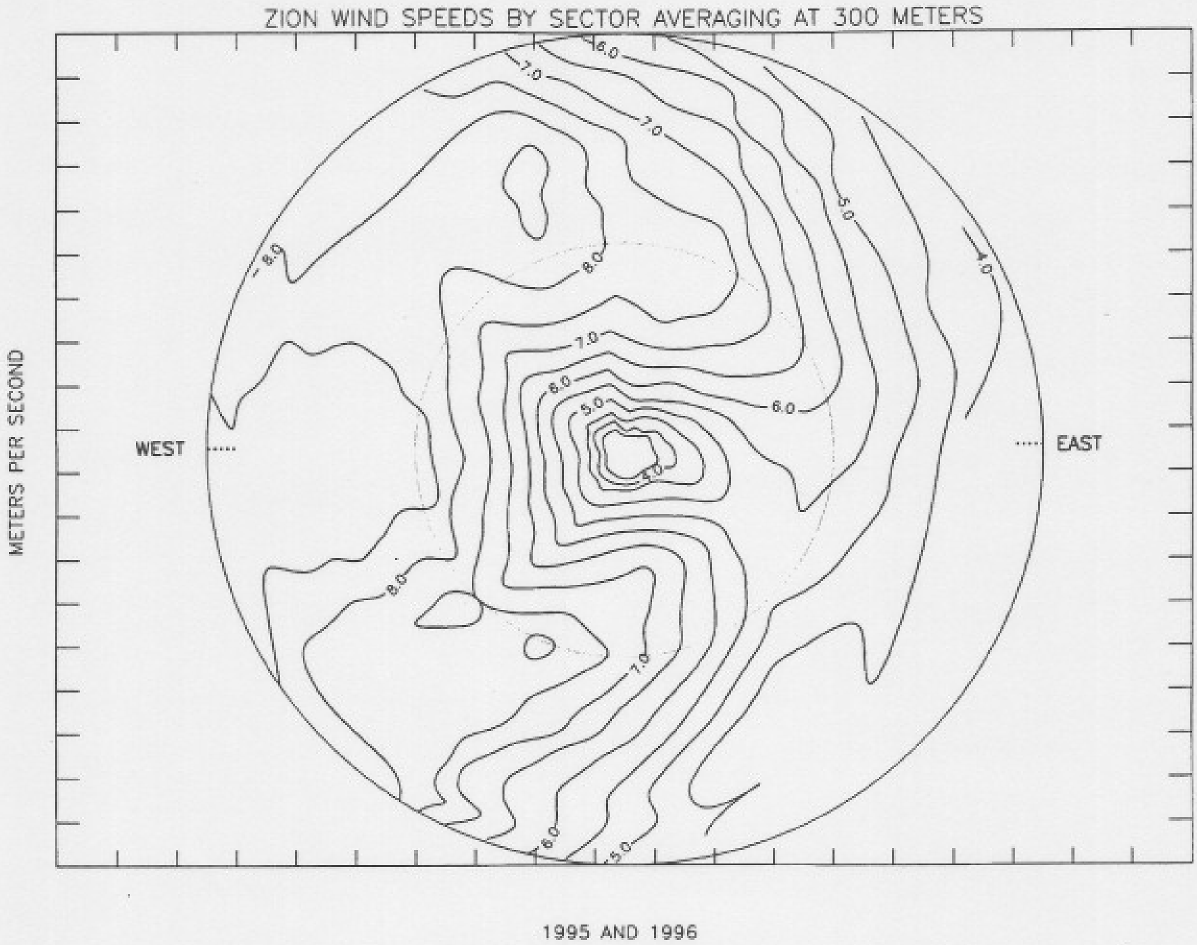

Figure 5. IDNS Doppler SODAR average wind speed data in meters per second for the wind profiles in Figure 3.

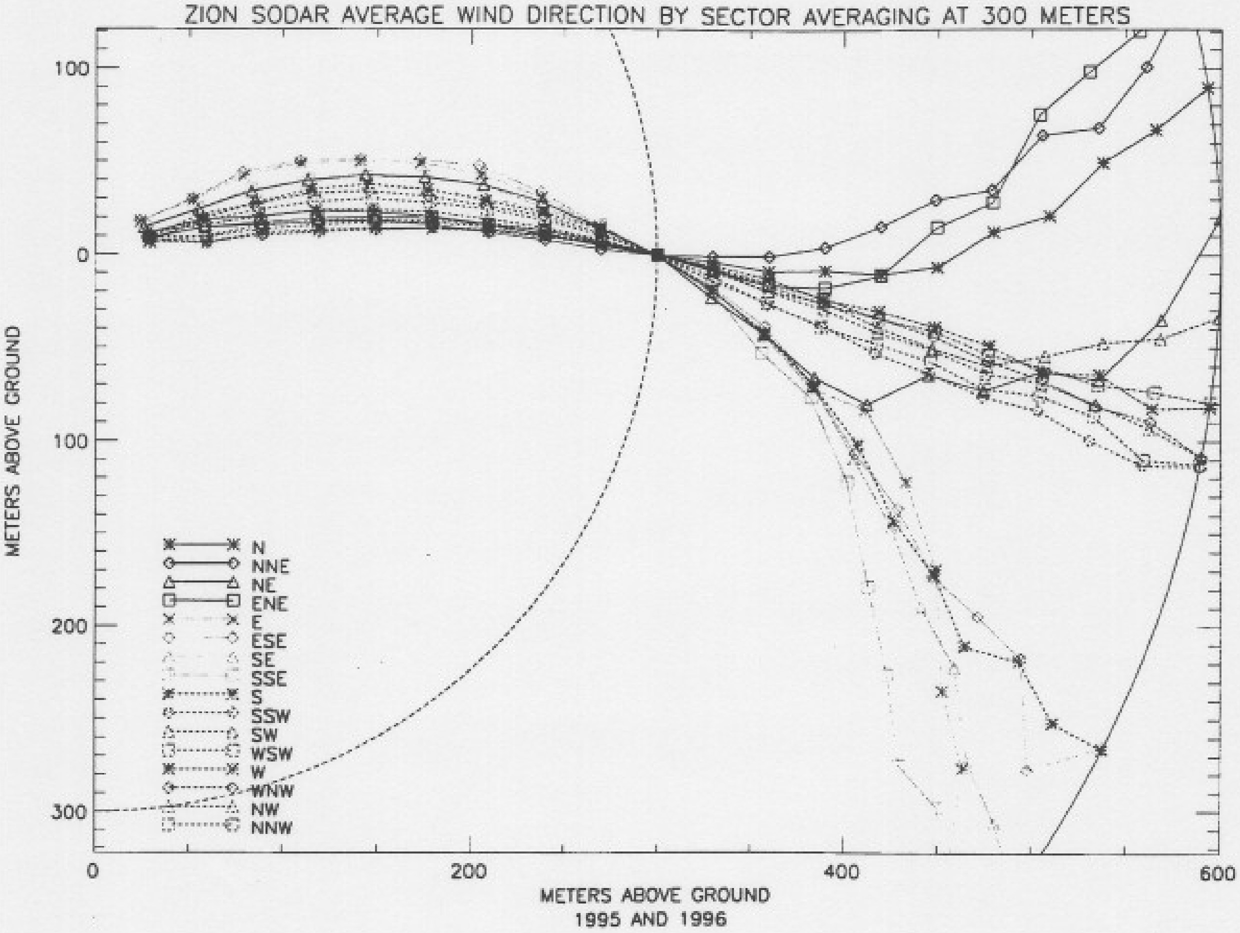

Figure 6. Same as Figure 3 data, only plotting all the curves in the same direction.

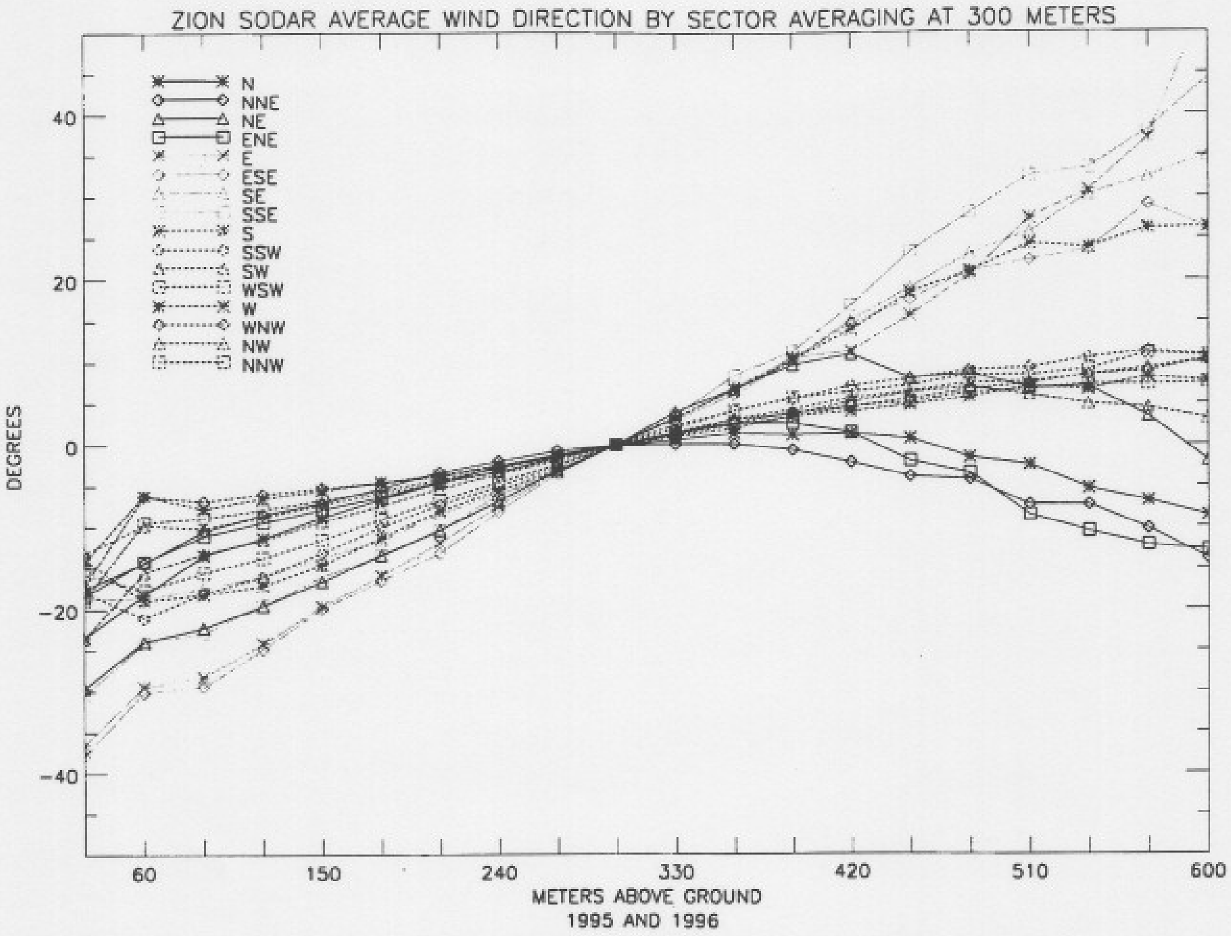

Figure 7. Same as Figure 3 data, only plotting all the curves on a linear scale.

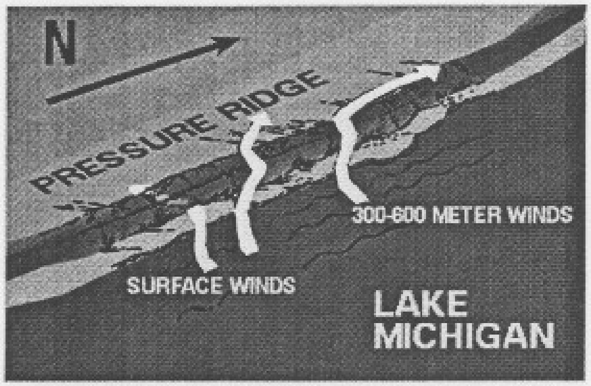

Figure 8. Wind direction changes with height due to the development of a pressure ridge caused by shoreline friction.

to the Coriolis effect. The figures can greatly help in determining plume transport, especially in areas where little meteorological data is available such as over the water.

The figures presented here could also help emergency responders with onshore frictional effects. The pressure ridge created by the shoreline surface friction during onshore flow could cause effluents carried aloft to travel in other directions than indicated by surface meteorological sites. The pressure ridge can be easily illustrated. Figure 10 shows a partially submerged log placed at an offset angle in a flowing stream. The log represents the pressure ridge along the shoreline, and the flow of water represents the wind from Lake Michigan. The log has a damming effect which causes the water to slow down and slightly raise in elevation upstream from the log. The water just ahead of the log responds by turning away from the log. This illustration would correspond to a southeast wind along the western shore of Lake Michigan with the 300- to 600-meter winds deflecting to a more southerly direction. Just the opposite is true for northeast winds.

The vertical velocity data presented in Figure 4 also shows basic synoptic meteorology. As low pressure systems move into the area, the wind shifts to a more easterly, southeasterly, and southerly direction. Since a low pressure system is characterized by ascending air, one would expect the east through south sectors to have rising motion as seen in Figure 4. As high pressure systems move into the area, the wind shifts to a more westerly, northwesterly, and northerly direction. Since a high pressure system is characterized by descending air, one would expect the west through north sectors to have sinking motion. The magnitude of the vertical motions may be useful to atmospheric modelers.

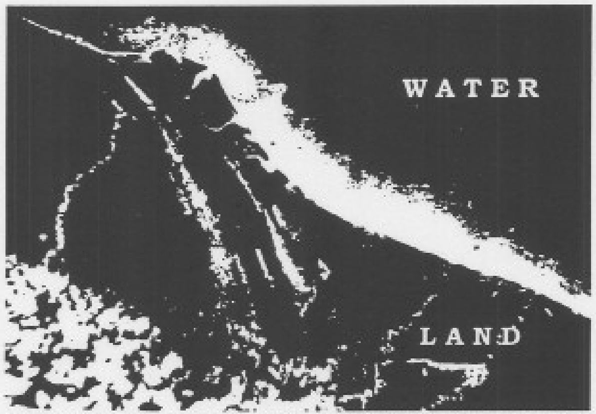

Figure 9. Manned spacecraft view of plumes along a coast

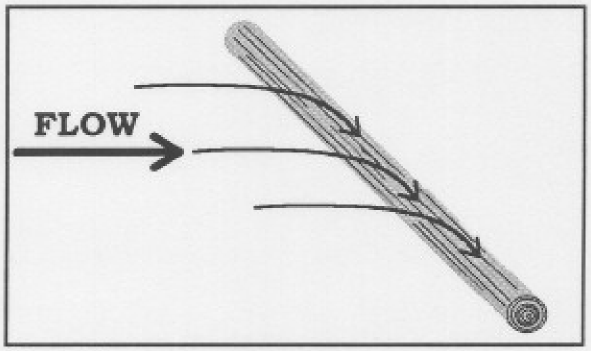

Figure 10.

6. SUMMARY

Terrain-induced friction can influence where effluents will travel along a coastline. Emergency responders could use the figures presented here to help determine the direction effluents will travel and help them better understand the meteorology along the shoreline.

7. REFERENCES

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